



Effects of shade trees on robusta coffee growth, yield and quality. A meta-analysis

Kevin Piato¹ · François Lefort² · Cristian Subía³ · Carlos Caicedo³ · Darío Calderón³ · Jimmy Pico³ · Lindsey Norgrove¹

© The Author(s) 2020

Abstract

Productivity of coffee plantations is threatened by both climate change and decreasing revenues of coffee growers. Using shade trees might protect against temperature variability, erosion and excessive radiation but there may be trade-offs in productivity and quality. While impacts of shade trees on arabica (*Coffea arabica*) have been reviewed, a global synthesis on robusta (*Coffea canephora*) coffee is lacking. We assessed how shade affects robusta growth and productivity, and what are the interactions and trade-offs. We conducted a systematic literature search in Web of Science and CAB Abstracts on 16 December 2019. Thirty papers fulfilled our inclusion criteria of being experimental studies on the impact of overstory trees with approximately half being from Brazil or India. Shade improved robusta tree growth and yield with some contrasting effects on physicochemical and biochemical properties. Shade (> 30%) was associated with reduced beverage quality. Significant interactions between shade and location, rainfall level and robusta clone were found. Among the clones tested, 06V, C153, LB1, GG229 and JM2 showed a higher productivity and growth (from + 17 to + 280%) under moderate shade (41–65%). This is the first meta-analysis of the effects of shade on robusta coffee. By synthesizing data from different studies, we highlight for the first time that the effect of shade on robusta coffee depends on tree age. Shade had positive impacts on older robusta trees (mean of 16 years), while the impact of shade on younger trees was either insignificant or negative. We highlight the importance of both clone type and tree ages. Research gaps included a lack of knowledge on the effects of shade with respect to coffee and shade tree age as well as interactive effects. More in-depth studies are needed to understand the mechanisms of how shade trees affect robusta coffee.

Keywords *Coffea canephora* · Agroforestry systems · Shade · Robusta coffee

1 Introduction

More than 9 billion kilogrammes of coffee are consumed annually worldwide (International Coffee Organization 2016).

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s13593-020-00642-3>) contains supplementary material, which is available to authorized users.

✉ Kevin Piato
kevinpiato1990@gmail.com; kevin.piato@students.bfh.ch

¹ School of Agricultural, Forest and Food Sciences (HAFL), Bern University of Applied Sciences (BFH), Länggasse 85, 3052 Zollikofen, Bern, Switzerland

² Plants and Pathogens Group, Research Institute Land Nature and Environment, HEPIA, HES-SO University of Applied Sciences and Arts Western Switzerland, Jussy, Geneva, Switzerland

³ National Institute of Agronomical Research (INIAP) - Central Experimental Station of Amazonia, km 3 Vía Sacha - San Carlos, Cantón Joya de los Sachas, Province of Orellana, Ecuador

The main coffee varieties produced and traded originate from the species *Coffea arabica* and *Coffea canephora*, which represent 65% and 35%, respectively, of global coffee production (International Coffee Organization 2016). Furthermore, the consumption of coffee is steadily increasing with an average annual growth rate of 1.3%, since the coffee production year 2012–2013 (International Coffee Organization 2016). The dissolution of the quota system provided for by the International Coffee Agreement (ICA) in 1989 caused large coffee price fluctuations and the emergence of large-scale plantations, especially in Vietnam (Waller et al. 2007). Large-scale intensive coffee production led to an increase in productivity per hectare resulting in reduction of shade trees inside the coffee agroecosystem, higher inputs costs (machinery, equipment, materials) and consequently higher break-even point (Rodríguez and Vasquez 2008).

Climate change is a threat to coffee production and may lead to coffee yield decline and loss of coffee-optimal areas, although it is currently unknown if there are new opportunities due to climate change, such as yield improvement through

elevated carbon concentration and potential increase in the area suitable for coffee production (Pham et al. 2019). Intensification of coffee production has been shown to exacerbate negative impacts of climate change (Lin et al. 2008). Furthermore, it has been shown that arabica coffee has already declined in Tanzania highlands and in India, owing to increasing temperatures (Craparo et al. 2015; Jayakumar et al. 2017). Robusta coffee yield may respond better to increasing temperatures than arabica coffee, although robusta coffee yield depends on the interaction of rainfall, temperature and phenological stage (Jayakumar et al. 2017; Kath et al. 2020). Although water supply is important for coffee production, it is difficult to know how future change in rainfall pattern will impact coffee production as the consolidated models of rainfall changes have a high degree of uncertainty given disparity in projections between individual models (Intergovernmental Panel on Climate Change 2019).

Pests and diseases are also a challenge for coffee growers and some are projected to cause more damage with climate change (Lambot et al. 2017). The main coffee pests include the coffee berry borer, *Hypothenemus hampei* (Ferrari) (Coleoptera: Curculionidae: Scolytinae), the coffee leaf miner, *Leucoptera coffeella* (Guérin-Méneville) (Lepidoptera: Lyonetiidae), and the brown twig beetle, *Xylosandrus morigerus* (Blandford) (Coleoptera: Curculionidae: Scolytinae). Coffee berry borer is the most destructive coffee pest worldwide (Rutherford and Phiri 2006; Vega et al. 2009), causing an estimated financial loss of US\$900 million annually only in Brazil alone (Oliveira et al. 2013). There are numerous fungal diseases of coffee, the most devastating one being coffee leaf rust caused by the basidiomycete fungus *Hemileia vastatrix* Berk. & Broome, American leaf spot of coffee caused by the basidiomycete fungus *Mycena citricolor* (Berk. & M. A. Curtis), cercospora leaf spot caused by the fungus *Cercospora coffeicola* Berk. & Cooke, thread blight caused by the fungus *Pellicularia koleroga* Cooke and coffee berry disease caused by the ascomycete fungus *Colletotrichum kahawae* J. M. Waller & Bridge. Coffee leaf rust is potentially the most damaging disease, since it can cause from 30 to 100% yield loss. In Central American coffee plantations, American leaf spot causes 20–30% yield loss (Waller et al. 2007). Cercospora leaf spot is a major coffee plant disease, reducing yields to less than 30%. Thread blight can cause yield losses of 70–80% in individually affected coffee plants and 10–20% in coffee plantations, while coffee berry disease crop losses in arabica coffee plantations may reach 20–30% in Africa, exceeding 80% in extremely wet years (Gaitán et al. 2015).

The inclusion of overstory trees in coffee crops could reconcile social, ecological and economic goals, although the study of their impact remains complex as the shade level depends on multiple parameters (Amoah et al. 1997). Coffee production under shade has been shown to be a mitigation strategy to cope with the harmful effects of climate change (Jaramillo et al. 2013;

Pham et al. 2019; The Intergovernmental Panel on Climate Change 2019), as shade can modify microclimate by reducing temperatures and reducing water loss through both lower soil evaporation and crop transpiration (Gomes et al. 2020; Jha et al. 2014; Lin 2010). Inclusion of shade (Vega et al. 2009) trees may also enhance other ecosystems services, such as carbon sequestration (Ehrenbergerová et al. 2016). Shaded coffee agroecosystems may also increase soil nutrient availability, through complementary partitioning of resources (Buchanan et al. 2019; Muñoz-Villers et al. 2020; Sauvadet et al. 2019). However, negative impacts of shade have also been reported on growth and yield, exacerbating pest and disease problems (Avelino et al. 2020; Durand-Bessart et al. 2020; Haggar et al. 2011; Jezeer et al. 2019). Equally, such adverse effects have also been highlighted for other tree crops such as cocoa (Beer et al. 1998). However, shade effects on coffee depend on the tree species used and the physical features of the site (Avelino et al. 2020; Sarmiento-Soler et al. 2020). Shade may reduce pest and disease damage through different physical and biological processes such as conservation or facilitation of the action of natural enemies, physical obstruction, stimulants and deterrents, resource dilution, disruption of the life cycle and allelopathy (Ratnadass et al. 2012). Staver et al. (2001) pointed out that multistrata coffee systems should be implemented in order to adapt the shade level with seasonal fluctuations, since humidity may play a key role in pest and disease regulation.

The effect of shade on coffee quality has been widely documented for arabica coffee and appear to be highly site-dependent (Tolessa et al. 2017). Bosselmann et al. (2009) found that shade negatively impacted cup quality of arabica in Southern Colombia, but did not affect bean size. On the contrary, Vaast et al. (2006) found that shade increased bean size and improved arabica cup quality in the central valley in Costa Rica. In this review, the effect of shade trees will be assessed only on robusta coffee, as the ecology (Davis et al. 2006; Nesper et al. 2017; Tumwebaze and Byakagaba 2016) and fertilization characteristics (Ferwerda 1948) differ between this species and the arabica coffee species. Treating both species together would have created confusion given different responses to shade (Beer et al. 1998; Cerda et al. 2017; Nesper et al. 2017). *C. arabica* is self-compatible, yet *C. canephora* coffee is self-incompatible and needs other clones and wind for successful pollination (Wintgens 2008). *C. arabica* yield has a biennial pattern, yet this pattern is less pronounced for *C. canephora* (Damatta et al. 2007). Furthermore, *C. arabica* and *C. canephora* may not have the same sensitivity to pests and diseases (Egonyu et al. 2017; Mariño et al. 2017), further highlighting the importance of dealing with these two species separately.

The aim of this review is to synthesize the currently known effects of shade trees on robusta coffee agroecosystem to understand better the complexity of the shade-plant interaction by disentangling the different factors involved (Fig. 1). We plan to identify which characteristics are influenced by shade.

Fig. 1 Robusta coffee plants growing in full-sun conditions (left) and under the overstory leguminous tree *Erythrina* spp. combined with plantains (right). Photo credit: Kevin Piatto



We anticipate that this synthesis will contribute towards experimental studies addressing the impact of overstory trees on robusta coffee plants in a general way and will assist in the setting up of new experimental trials in this field. Furthermore, this synthesis will provide recommendations to farmers willing to integrate shade trees in robusta coffee crop system.

2 Methodology

We followed a standard systematic review methodology based on Foli et al. (2014). We conducted a literature search in Web of Science and CAB Abstracts on 16 December 2019 by searching for the following combinations of words in the topic field (Web of Science) and in all fields (CAB Abstracts): (agroforestry OR “agroforestry system*” OR “shaded coffee” OR “full sun” OR “unshaded coffee” OR “tropical agroforest*” OR agroecosystem* OR “coffee agro-ecosystem*” OR agroforest* OR shade* OR open-grown OR “shaded system*” OR “unshaded system*”) AND (“robusta coffee” OR “*Coffea canephora*” OR “conilon coffee” OR “*Coffea robusta*” OR “*C. canephora*”). We have chosen these two databases since they cover a large proportion of the peer-reviewed literature, providing a quality control standard. All searches were conducted in English and covered publication years from 1900 to 2019 (Web of Science) and from 1912 to 2020 (CAB Abstracts).

2.1 Data exclusion criteria

We assessed articles by analysing abstracts following the *Preferred Reporting Items for Systematic Reviews and Meta-Analyses* (PRISMA, Moher et al. 2009) (Appendix S1, Fig. S1). The initial search resulted in 162 publications. The publications were first screened by title according to the following exclusion criteria: review, inventory, interview, questionnaire. Furthermore, double titles were removed. This screening resulted in 147 publications (15 removed). Secondly, remaining publications were screened by abstract with the following exclusion criteria: review, inventory, interview, questionnaire, no

abstract, no obvious link between coffee and shade, arabica coffee only, thesis, project, intercropping of coffee plants only with ground-level crops (such as vegetables). This screening resulted in 73 publications (74 removed). Finally, remaining publications were screened using the full text according to the following exclusion criteria: interview/questionnaire as the main process of data acquisition, no obvious relation with shade, observational units not based on robusta coffee plants or environment, paper not available after extensive acquisition attempt, paper unclear, intercropping of coffee plants only with ground-level crops (such as vegetables). This last screening left 30 papers (44 removed). These specific screening steps have been achieved to extract all the papers dealing with the impact of overstory trees on robusta coffee crop or ecology based on experimental or observational studies collecting data through measurements. References were not screened by type of statistical analysis used.

2.2 Data extraction and handling

We used Citavi 6.3.15.0 software (Swiss Academic Software 2019) to import and classify the included studies. Variables of interest used for classification were (1) country; (2) climate (Köppen classification); (3) altitude; (4) soil type; (5) study design (experimental or observational); (6) treatments assessed (factors, control, number); (7) observational unit; (8) robusta coffee plants and shade trees age; (9) duration of the study; (10) response variables; (11) statistical analysis; (12) single factors significant outcomes (i.e. $P < 0.05$, here and throughout the text); (12) significant interaction between factors; (13) significant correlation between response variables and further research needed. In addition, each item was qualified according to the type of impact of shade trees on growth, yield and coffee quality. “Negative” was used when the paper reported that the inclusion of shade inside the robusta coffee field may be significantly detrimental to the quality, growth or productivity of coffee plants. “Inconclusive” was used when the paper reported both significantly detrimental and significantly beneficial effects. “Positive” was used when the paper reported significant benefits. Among the factors,

shade was separated into three groups: shading method, shading level and shade tree type. Shading “method” refers to either the shade tree species or the number of tree species included in the system, whereas shading “level” refers to the quantity of shade. Shade tree type refers to different type of trees used in each treatment (as deciduous and evergreen trees, young and old trees, native and exotic trees).

All statistical analysis were performed in R studio Version 1.1.463 (R Core Team 2019). Rmisc package (Hope 2013) was used to compute descriptive statistics. Furthermore, ggplot2 (Wickham 2016), egg (Auguie 2019) and PerformanceAnalytics (Peterson and Carl 2019) packages were used to create the graphics. ArcGIS Version 10.6.1 was used for mapping (Environmental Systems Research Institute 2018).

3 Results and discussion

3.1 Global distribution of shade tree and robusta studies

Clear trends can be seen from the 30 selected articles. In terms of geographical distribution, Brazil ($n = 9$) and India ($n = 7$) were the countries yielding the most studies (Fig. 2). It is interesting to note that none of the studies came from Vietnam, although it is the largest robusta coffee producer worldwide (Amarasinghe et al. 2015). The number of studies selected for Indonesia ($n = 2$) does not reflect the importance of this country in terms of world coffee production

(Food and Agriculture Organization of the United Nations 2020). Both studies in USA were from Puerto Rico (Prado et al. 2018, 2019). According to Köppen’s classification (Beck et al. 2018), the climates encountered in the studies were (1) Tropical-Rainforest (Af, $n = 6$), (2) Tropical-Monsoon (Am, $n = 7$) and (3) Tropical-Savannah (Aw, $n = 17$). Among the studies, one was conducted under greenhouse conditions (Avinash Kumar et al. 2015).

Shading method ($n = 14$) and shading level ($n = 12$) were the most frequently evaluated factors (Fig. 3). Other factors unrelated with shade are also assessed such as farming practices ($n = 3$) which included irrigation type and level, fertilization and pollination type. Among the shading methods, 26 shade tree species were considered. The following species were most frequently evaluated: *Albizia* spp. (Fabaceae), *Artocarpus heterophyllus* (Moraceae), *Erythrina* spp. (Fabaceae), *Ficus* spp. (Moraceae), *Gliricidia* spp. (Fabaceae) and *Michelia champaca* (Magnoliaceae). Ecological factors ($n = 6$) included soil depth, rainfall level and location suitability. Eighty-three percent of the studies assessing shading level impact on robusta coffee found significant effects (Fig. 3). The only study assessing the impact of coffee plant density failed to find significant results (Amoah et al. 1997).

Additionally, the number of response variables per study was strongly positively correlated with the number of significant response variables per study ($p < 0.001$). Studies that included more response variables had more statistically

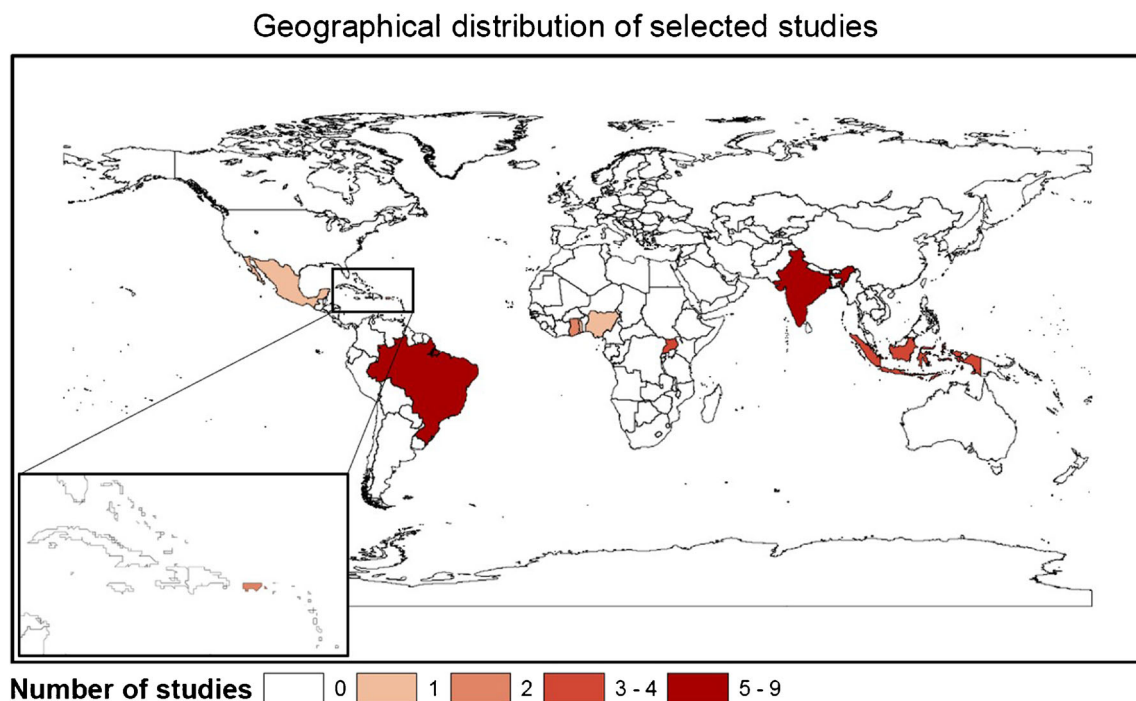


Fig. 2 Map depicting the number of selected studies grouped by country. The country is understood as the location of the field site ($n=30$; see “References of the meta-analysis” at end of paper)

significant results. This shows that the impact of shade on the development of robusta coffee is complex and multidisciplinary studies are better able to capture this impact. Coffee age and shade tree age were also strongly positively correlated ($p < 0.001$), meaning that both coffee plants and shade trees were planted at the same time (Fig. 4).

Each study was categorized according to its conclusion about the inclusion of shade trees in robusta coffee plantations (“positive”, “inconclusive” and “negative”). These feedback groups were then characterized (Fig. 5). Positive studies clearly show higher coffee age (13.95 ± 9.06 , “ \pm ” refers to 1.96 SE here and throughout the text) and older coffee trees (15.93 ± 10.25) than those with inconclusive (8.36 ± 5.63 and 8.7 ± 6.64 respectively) or negative effects (7 ± 1.96 and 6 ± 1.96 respectively). The same trend can be highlighted for the number of interactions (only significant) being slightly higher for positive studies (1.47 ± 1.29) than inconclusive (1.2 ± 1.08) and negative (1 ± 1.96) ones. Papers reporting longer-term studies were more likely to find trade-offs, i.e. both significant negative and positive effects (inconclusive studies, 2.08 years ± 1.29) than those of shorter duration. Mean length of the 30 screened studies was 1.32 years. Although the 95% confidence interval error bars are overlapping for each of these groupings, this highlights the need for further studies on the impact of shade trees on robusta coffee.

3.2 Effect of shade trees on robusta growth and productivity parameters without interacting factors

In six experiments, shade impacted positively both growth and productivity of robusta coffee (Table 1). Nevertheless,

Venancio et al. (2019) found that shade reduced the average number of fruits per inflorescence, suggesting that vegetative growth may compete with fruit production. However, this might not necessarily reduce yield, as no study was found in which shade significantly reduced robusta yield. Furthermore, Venancio et al. (2019) showed that medium shade levels (i.e. 30–50%) may increase the proportion of cherries that are marketable.

3.3 Effect of shade trees on robusta growth and productivity parameters with interacting factors

In five out of 30 experiments, the effect of shade trees on coffee growth and productivity interacted with other variables, namely cultivar (Assis et al. 2019; Rodriguez-Lopez et al. 2013; Venancio et al. 2019), location suitability (Amoah et al. 1997) and pollination type (Prado et al. 2018). However, most frequently, the type of robusta clone interacted with shade level (Assis et al. 2019; Venancio et al. 2019). The amount of shade required to obtain the maximum robusta growth and productivity varied according to the type of clone tested (Table 2).

All the clones assessed for growth and productivity responded positively to shade. However, productivity and growth were not necessarily correlated. For some clones, the highest productivity was obtained with higher shade levels than those required to maximize growth (C153, LB1, GG229 and JM2), while for others it was the opposite (03V, 06V and 12V). For 03V, 06V and 12V clones, it might be that growth is not correlated with productivity or that vegetative and reproductive growth compete. Shade had different effects per clone on growth and yield. Clones 06V, C153, LB1, GG229 and JM2 could be advisable if growing robusta coffee as an understory crop.

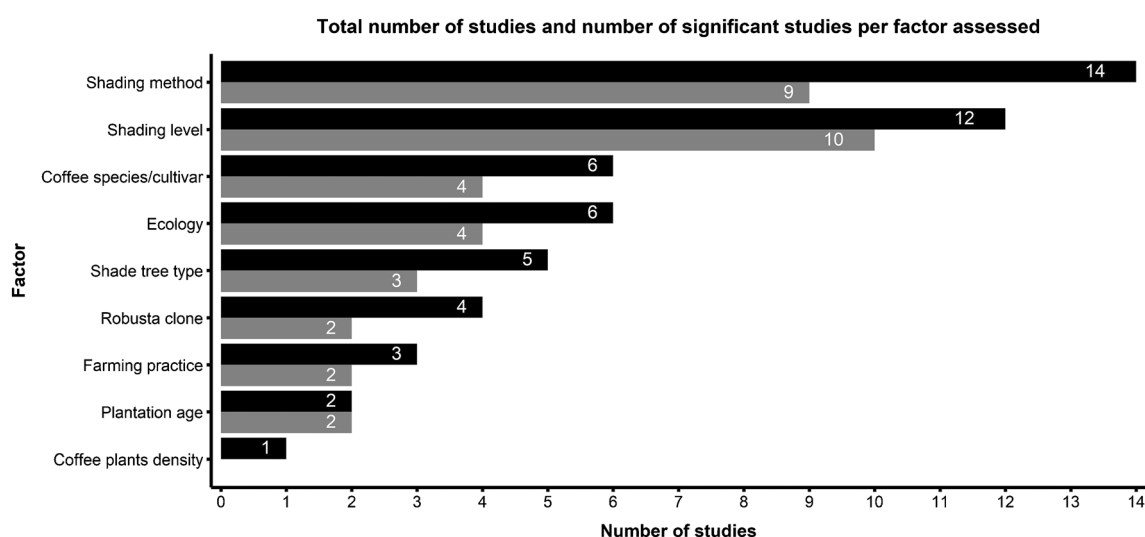


Fig. 3 Bar chart depicting the number of studies grouped by type of factor assessed. Total number of studies per factor (black) and number

of studies that have found significant results with the respective factor (grey) are represented

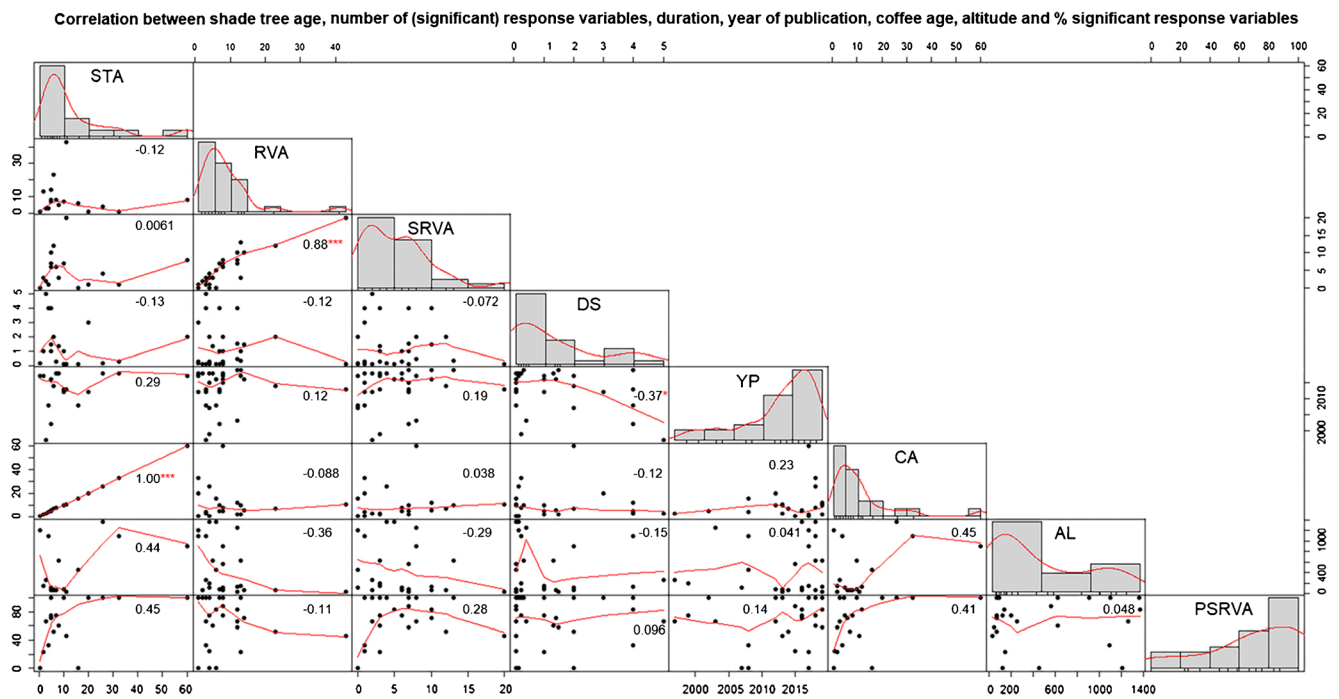


Fig. 4 Correlation matrix depicting the correlation between the shade tree age (STA), the number of response variables per study (RVA), the number of significant response variables per study (SRVA), the duration of the study (DS), the year of publication (YP), the coffee age (CA), the altitude (AL) and the % of significant response variables per

study (PSRVA). Across the diagonal histograms with kernel density and rug plots are shown and below the diagonal scatter plots with fitted lines. Pearson correlation coefficients with significance level ($<0.001^{***}$; $<0.01^{**}$; $<0.05^{*}$) are shown at the right corner of each scatter plot

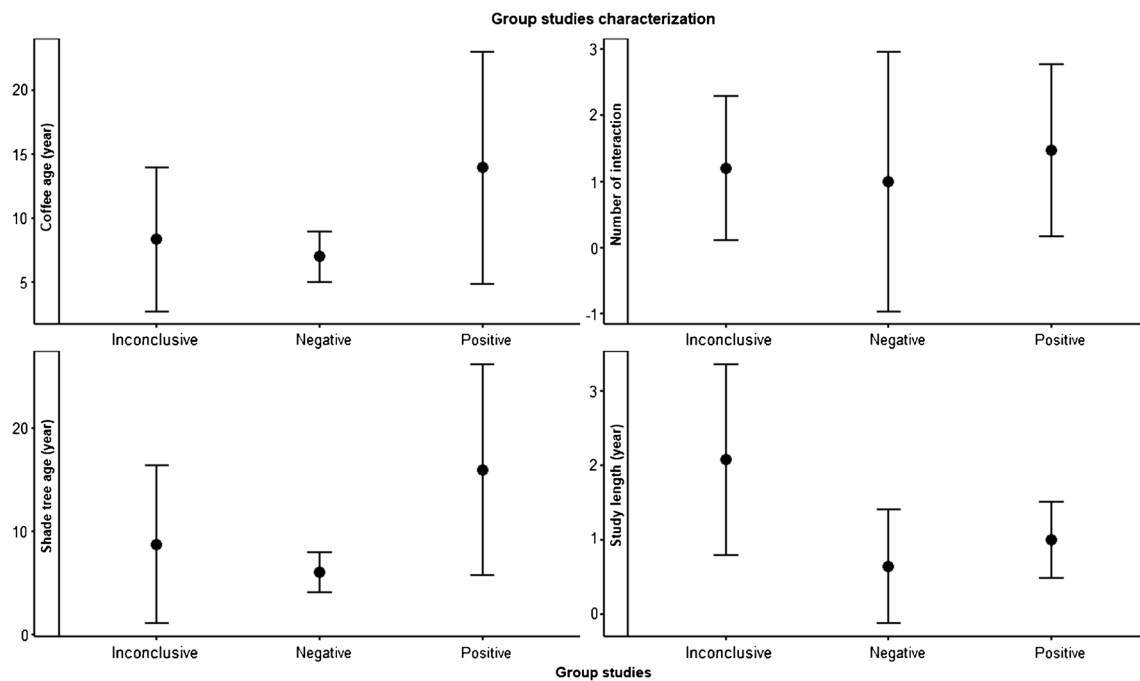


Fig. 5 $M(\text{dot}) \pm 1.96 \text{ SE}$ (a) coffee age (years); (b) number of interactions; (c) study length (year); (d) coffee age (year) for the negative (shade is detrimental for coffee plant), inconclusive (shade is

both detrimental and beneficial for coffee plant) and positive (shade is beneficial for coffee plant) groups studies

Table 1 Number of studies reporting either positive, negative or inconclusive impacts of shading method and shading level on robusta growth and productivity without interacting factors

	Response variables	Shading method			Shading level		
		Positive impact	Negative impact	Inconclusive impact	Positive impact	Negative impact	Inconclusive impact
Growth	Internode length of plagiotropic or orthotropic branches (mm)	2			3		
	Internode length of fruit-bearing plagiotropic branches (cm)	1			1		
	Internode length of tip of productive plagiotropic branches (cm)	1			1		
	Accumulated growth of orthotropic branches (cm)				1		
	Leaf area or leaf expansion (cm ²)	1			2		
	Specific leaf area (cm ² g ⁻¹)				1		
	Total number of growth studies	5	0	0	9	0	0
Productivity	No. of fruits: no. of marketable fruits per plant ratio						1
	Average no. of fruits per inflorescence					1	
	Yield (kg ha ⁻¹)	2	1				
	Total number of Productivity Studies	2	1	0	0	1	1
	Total number of Studies	7	1	0	9	1	1
	References	[1]; [5]; [6]	[1]		[2]; [3]; [4]	[4]	[4]

[1] Araujo et al. 2016; [2] Oliosi et al. 2016; [3] Partelli et al. 2014; [4] Venancio et al. 2019; [5] Evizal et al. 2013; [6] Evizal et al. 2012

3.4 Effects of shade trees on physicochemical, physiological, biochemical and photosynthetic parameters of robusta without interacting factors

In 10 out of 30 experiments, shade trees had significant impacts on at least one physicochemical, physiological, biochemical or photosynthetic variable (Table 3). Shade impacts on physicochemical properties of robusta coffee did not follow a clear trend, although negative results account for 48% of the total results versus 40% for positive results (including both shading method and level factors). This apparent contradiction could be explained by the presence of underlying interactions not considered (cf. section 3.5). Biochemical properties were clearly

negatively affected by the presence of shade trees. Physiological and photosynthetic variables were positively impacted by the shade, albeit there were few studies evaluating these.

3.5 Effects of shade trees on robusta physicochemical, physiological and photosynthetic parameters with interacting factors

In 3 out of 30 experiments, the effect of overstory trees on coffee physicochemical, physiological and photosynthetic parameters interacted with robusta clones and in some cases there were comparisons with the arabica species (Anim-

Table 2 Shade level required to obtain the highest growth and productivity of some robusta clones (Assis et al. 2019; Venancio et al. 2019)

Clone	C153	LB1	GG229	JM2	03V	06V	12V
% of shade with highest growth ^{1,2}	54	50	60	60	26	59	33
% of shade with highest productivity ^{3,4}	70	70	70	70	7	23	10

¹ For C153, LB1, GG and JM2 clones, mean of % of shade with the highest plant height, collar diameter, length of main branch, crown diameter and number of plagiotropic branches is depicted

² For 03V, 06V and 12V clones, mean of % of shade with the highest mean orthotropic and plagiotropic branch growth rate and plagiotropic branch node emission rate is depicted

³ For C153, LB1, GG and JM2 clones, % of shade with the highest number of fruits is depicted

⁴ For 03V, 06V and 12V clones, mean of % of shade with highest number of inflorescences per productive plagiotropic branch, mean number of fruits per inflorescence, total fruit production per plant and total fruit production per plant benefited is depicted

Table 3 Number of studies reporting either positive, negative or inconclusive impacts of shading method and shading level on robusta physicochemical, physiological, biochemical and photosynthetic parameters without interacting factors

	Response variables	Shading method			Shading level		
		Positive impact	Negative impact	Inconclusive impact	Positive impact	Negative impact	Inconclusive impact
Physicochemical	Leaf nutrient, chlorophyll content (g kg^{-1})	4	2		3	4	1
	Fruit leached K, total sugar, chlorogenic acid and leaf caffeine content (g kg^{-1})		4			1	
	Leaf water potential (MPa), fruit electrical conductivity ($\mu\text{S cm}^{-1}$)		1	1			
Physiological	Total number of physicochemical studies	4	7	1	3	5	1
	Leaf thickness (μm), corolla diameter (mm), % of dead non-rooted cuttings				2	1	
	Total number of physiological studies	0	0	0	2	1	0
Biochemical and Photosynthetic	Activity of superoxide dismutase ($\text{kU min}^{-1} \text{g}^{-1}$), catalase, ascorbate peroxidase, glutathione reductase ($\mu\text{mol min}^{-1} \text{g}^{-1}$)		4				
	Carbon assimilation ($\mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$), stomatal conductance and transpiration rate ($\text{mmol H}_2\text{O m}^{-2} \text{s}^{-1}$), photosynthetic N use efficiency ($\mu\text{mol CO}_2 \text{g}^{-1} \text{N s}^{-1}$)	1		3			
	Total number of biochemical and photosynthetic studies	1	4	3	0	0	0
	Total number of studies	5	11	4	5	6	1
	References	[1]; [5]; [7]	[1]; [2]; [3]; [7]	[7]	[6]; [8]; [9]	[2]; [4]; [9]	[2]

[1] Araujo et al. 2016; [2] Partelli et al. 2014; [3] Alves et al. 2018; [4] Avinash Kumar et al. 2015; [5] Evizal et al. 2012; [6] Prado et al. 2019; [7] Rodriguez-Lopez et al. 2013; [8] Assis et al. 2019; [9] Anim-Kwapong et al. 1999

Kwapong et al. 1999; Prado et al. 2019; Rodriguez-Lopez et al. 2013). For robusta clone 03, leaf chlorophyll and carotenoid concentrations increased with morning shade, yet there was no effect on clone 120. Equally, leaf chlorophyll-to-carotenoid ratio of robusta clone 03 was higher showing improved health under morning shade (Rodriguez-Lopez et al. 2013). Leaf chlorophyll-to-carotenoid ratio is an important indicator of plant light stress (You et al. 2017) and increasing carotenoid leaf content is known to be an acclimation to shade to increase light absorption (Czeczuga 1987).

3.6 Effects of shade trees on robusta ecological and microclimatic parameters without interacting factors

In 6 out of 30 experiments, shade altered ecological and microclimatic factors in a favourable way for coffee by decreasing extreme temperatures and reducing hydric stress by increasing relative humidity, favouring growth and the development of soil microorganisms (Partelli et al. 2014). However, more than a third of the ecological parameters (Table 4) of robusta coffee were impacted in both positive and negative ways by the presence of shade, showing that the trade-off is inherent to agroforests to satisfy dual production and ecological goals, a tendency also shown for other crops, such as

cocoa (Blaser et al. 2018). Not only does the shade affect agrobiodiversity but also the land use intensity (Klein et al. 2002). This could be one of the reasons why the mere presence of shade has not shown a conclusive effect on the ecological parameters of robusta coffee systems.

3.7 Effects of shade trees on robusta coffee quality and phytosanitary parameters without interacting factors

Coffee crops are prone to many pests and diseases that can significantly reduce productivity. Few articles dealt with the impact of shade on robusta coffee pests and diseases. Shade tree type has been shown to impact significantly the infestation of black coffee twig borer, *Xylosandrus compactus* (Eichhoff), a pest which severely affects robusta coffee plantations, especially in Uganda (Bukomeko et al. 2018). Bukomeko et al. (2018) showed that mature shade trees and sap-exuding herbaceous plants such as *Carica papaya* could significantly reduce black coffee twig borer on robusta coffee plants as well as an increasing number of sap exuding trees (shading level). Impact of 0 to 30% shade on robusta cup taste (on a 0–10 scale) was not significant, yet more than 30% shade reduces it significantly (Vaast and Raghuramulu 2012).

Table 4 Number of studies reporting either positive, negative or inconclusive impacts of shading method, shading level and shade tree type on robusta ecological and microclimatic parameters without interacting factors

	Response variables	Shading method and shade tree type				Shading level			
		Positive impact	Negative impact	Inconclusive impact		Positive impact	Negative impact	Inconclusive impact	
Ecological	Root colonization by arbuscular mycorrhizal fungi (%)	1		1					
	Aboveground shade tree C stock (Mg ha^{-1})		1						
	No. of Braconidae parasitoid wasps, Chalcidae parasitoid wasps, eumenid wasps, species in trap nest, flower-visiting solitary and social bees, drosophilid flies	6		3					
	Soil bacteria ($\text{cfu } 10^4 \text{ g}^{-1} \text{ soil}$) and diversity (Shannon-Weaver index)	4		4					
	Soil fungi ($\text{cfu } 10^3 \text{ g}^{-1} \text{ soil}$) and actinomycetes ($\text{cfu } 10^4 \text{ g}^{-1} \text{ soil}$)	2							
Microclimatic	Soil organic carbon (t ha^{-1})	1							
	Soil microporosity and total porosity ($\text{m}^3 \text{ m}^{-3}$)	2							
	Total number of ecological studies	16	1	8		0	0	0	0
	Irradiance ($\mu\text{mol m}^{-2} \text{ s}^{-1}$), relative humidity (%)					1	1	1	
	Total number of microclimatic studies	0	0	0		1	1	1	0
	Total number of studies	16	1	8		1	1	1	0
	References	[1–4]; [5]*; [6]; [7]; [8]							

[1] Souza et al. 2017; [2] Tumwebaze and Byakagaba 2016; [3] Bagyaraj et al. 2015; [4] Evizal et al. 2013; [5] Klein et al. 2002; [6] Evizal et al. 2012; [7] Guillemot et al. 2018; [8] Oliosi et al. 2016

*This study was performed during *La Niña*. Thus, the results may be impacted by this phenomenon and should be considered with caution

3.8 Effects of shade trees on robusta coffee quality parameters with interacting factors

Vaast and Raghuramulu (2012) showed that the effect of over-story trees on % of AA category beans ($> 7\text{-mm}$ diameter) depends on rainfall at the site (Vaast and Raghuramulu 2012). Under low rainfall conditions, robusta bushes intercropped with *Artocarpus heterophyllus*, *Dalbergia latifolia* and *Lagerstroemia microcarpa* trees provide a higher % of AA category beans than those intercropped with *Grevillea robusta*. Under high rainfall, coffee intercropped with *A. heterophyllus* or *G. robusta* provided lower % of AA category beans. Under high rainfall, robusta intercropped with *A. heterophyllus*, *D. latifolia* and *L. microcarpa* trees provided a better cup taste than those intercropped with *G. robusta*.

3.9 Limitations of the study

The effects of shade on coffee can be site-specific thus depending upon the clone selected and the site conditions (Montagnon et al. 2000). Yet selected studies did not consider site differences. Further studies should be multilocal thus identifying the most suitable shade and clone coupling for the site conditions. Concerning the significant correlation between the number of response variables per study (RVA) and the number of significant response variables per study (SRVA), it is unlikely that this could represent a confounding effect with the shade, since the selected papers all had randomized experimental designs (papers describing observational studies were rejected). Thus, they are fairly comparable, the randomization allowing to reduce the link between shade, RVA and SRVA (Pourhoseingholi et al. 2012; Valentine and Thompson 2013). The correlation found between the shade tree age and the coffee plant age could be modified by the farming practice employed, but the ages have not always been documented in the papers. Biennial yield fluctuation is less pronounced for robusta than for arabica coffee. The authors of selected papers have not always included this aspect in the analysis. However, as shade is known to reduce biennial fluctuation of yield (Damatta 2004) and as yield has generally been measured among several years, this should not constitute a bias.

4 Conclusion

In this meta-analysis, based on 30 peer-reviewed studies, we found that shade trees positively impacted growth, yield, physiological, photosynthetic, ecological and microclimatic variables of robusta coffee plants. However, biochemical variables were somehow negatively impacted. Beverage quality and physicochemical properties were unevenly influenced. Significant interactions between shade and location, rainfall

level, robusta clones, pollination type and coffee species were found. The choice of robusta clones was an important interactive factor. All the clones tested responded positively to shade. Clones 06V, C153, LB1, GG229 and JM2 showed a higher productivity and growth under significant amount of shade (41–65%). These clones can therefore be recommended for shade systems and farmers are likely to be interested in integrating shade trees with these clones as shade increases robusta coffee yield. Clones 06V, C153, LB1, GG229 and JM2 showed a higher productivity and growth under significant amounts of shade (41–65%). We can preferably recommend the clone 06V under tropical-savannah climate (Aw), i.e. under climate with a pronounced dry season. Regarding the C153, LB1, GG229 and JM2 clones, they should be preferably used in tropical-rainforest climatic conditions (Af), i.e. with no pronounced dry season. Furthermore, no intense shade should be implemented in the robusta coffee systems as it may negatively affect cup quality. We also demonstrated the importance of considering the type of clone, the coffee age and shade tree age when assessing shade effects on robusta. Coffee trees of at least 10 years old were more positively impacted by shade.

Empirical studies on the shade impact on robusta coffee plants are notoriously few, especially those considering interaction between shade trees and the parameters, such as the type of farming practices, the area, the climate and soil type. Further research is also needed to assess the impact of microclimatic variables on pests and diseases development (Bukomeko et al. 2018). Shade tree management has to be fine-tuned to optimize nutrient cycling and avoid nutrient immobilization. Furthermore, the role of shade trees in carbon storage and cycling has to be better understood (Guillemot et al. 2018). More research is required to better understand biological control mechanisms in robusta agroforestry systems, with a particular emphasis carrying on the relationships between the shade trees, the coffee plants, the pests and diseases and their natural enemies under varying abiotic variables (Hajian-Forooshani et al. 2018).

Acknowledgements We acknowledge the helpful comments of the anonymous reviewers and the editors in improving the quality of the paper.

Compliance with ethical standards

Funding This review was funded by the HES-SO University of applied sciences and arts of western Switzerland, the Bern University of Applied Sciences (BFH) in Switzerland and the National Institute of Agronomical Research (INIAP) in Ecuador.

Conflict of interest The authors declare that they have no conflict of interest.

Author contribution Conceptualization—K.P., F.L., C.S., C.C., D.C., J.P., L.N.; analysis—K.P.; interpretation—K.P., L.N.; writing—original draft—K.P.; writing—review and editing—K.P., L.N., F.L. C.S. C.C. D.C., J.P.; supervision—L.N., F.L.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Amarasinghe UA, Hoanh CT, D'haeze D, Hung TQ (2015) Toward sustainable coffee production in Vietnam: more coffee with less water. *Agric Syst* 136:96–105. <https://doi.org/10.1016/j.agry.2015.02.008>
- Auguie B (2019) egg: extensions for “ggplot2”: custom geom, custom themes, plot alignment, labelled panels, symmetric scales, and fixed panel size. R package version 0.4.5. <https://CRAN.R-project.org/package=egg>
- Avelino J, Vilchez S, Segura-Escobar MB, Brenes-Loaiza MA, Virginio Filho EM, Casanoves F (2020) Shade tree *Chloroleucon eurycyllum* promotes coffee leaf rust by reducing uredospore wash-off by rain. *Crop Prot* 129:1–8. <https://doi.org/10.1016/j.cropro.2019.105038>
- Beck HE, Zimmermann NE, McVicar TR, Vergopolan N, Berg A, Wood EF (2018) Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Sci Data* 5:180214. <https://doi.org/10.1038/sdata.2018.214>
- Beer J, Muschler R, Kass D, Somarriba E (1998) Shade management in coffee and cacao plantations. *Agrofor Syst* 38:139–164. <https://doi.org/10.1023/A:1005956528316>
- Blaser WJ, Oppong J, Hart SP, Landolt J, Yeboah E, Six J (2018) Climate-smart sustainable agriculture in low-to-intermediate shade agroforests. *Nat Sustain* 1:234–239. <https://doi.org/10.1038/s41893-018-0062-8>
- Bosselmann AS, Dons K, Oberthur T, Olsen CS, Ræbild A, Usma H (2009) The influence of shade trees on coffee quality in small holder coffee agroforestry systems in Southern Colombia. *Agric Ecosyst Environ* 129:253–260. <https://doi.org/10.1016/j.agee.2008.09.004>
- Buchanan S, Isaac ME, van den Meersche K, Martin AR (2019) Functional traits of coffee along a shade and fertility gradient in coffee agroforestry systems. *Agrofor Syst* 93:1261–1273. <https://doi.org/10.1007/s10457-018-0239-1>
- Cerda R, Allinne C, Gary C, Tixier P, Harvey CA, Krolczyk L, Mathiot C, Clément E, Aubertot J-N, Avelino J (2017) Effects of shade, altitude and management on multiple ecosystem services in coffee agroecosystems. *Eur J Agron* 82:308–319. <https://doi.org/10.1016/j.eja.2016.09.019>
- Craparo ACW, van Asten PJA, Läderach P, Jassogne LTP, Grab SW (2015) *Coffea arabica* yields decline in Tanzania due to climate change: global implications. *Agric For Meteorol* 207:1–10. <https://doi.org/10.1016/j.agrformet.2015.03.005>
- Czeczuga B (1987) Carotenoid contents in leaves grown under various light intensities. *Biochem Syst Ecol* 15:523–527. [https://doi.org/10.1016/0305-1978\(87\)90098-6](https://doi.org/10.1016/0305-1978(87)90098-6)

- Damatta FM (2004) Ecophysiological constraints on the production of shaded and unshaded coffee: a review. *Field Crops Res* 86:99–114. <https://doi.org/10.1016/j.fcr.2003.09.001>
- Damatta FM, Ronchi CP, Maestri M, Barros RS (2007) Ecophysiology of coffee growth and production. *Braz J Plant Physiol* 19:485–510. <https://doi.org/10.1590/S1677-04202007000400014>
- Davis A, Govaerts R, Bridson D, Stoffelen P (2006) An annotated taxonomic conspectus of the genus *Coffea* (Rubiaceae). *Bot J Linn Soc* 152:465–512. <https://doi.org/10.1111/j.1095-8339.2006.00584.x>
- Durand-Bessart C, Tixier P, Quinteros A, Andreotti F, Rapidel B, Tauvel C, Allinne C (2020) Analysis of interactions amongst shade trees, coffee foliar diseases and coffee yield in multistrata agroforestry systems. *Crop Prot* 133:105137. <https://doi.org/10.1016/j.cropro.2020.105137>
- Ehrenbergerová L, Cienciala E, Kučera A, Guy L, Habrová H (2016) Carbon stock in agroforestry coffee plantations with different shade trees in Villa Rica, Peru. *Agrofor Syst* 90:433–445. <https://doi.org/10.1007/s10457-015-9865-z>
- Environmental systems research institute (2018) ArcGIS desktop. <http://www.esri.com>
- Ferwerda FP (1948) Coffee breeding in Java. *Econ Bot* 2:258–272
- Foli S, Reed J, Clendenning J, Petrokofsky G, Padoch C, Sunderland T (2014) To what extent does the presence of forests and trees contribute to food production in humid and dry forest landscapes?: a systematic review protocol. *Environ Evid* 3:15. <https://doi.org/10.1186/2047-2382-3-15>
- Food and Agriculture Organization of the United Nations (2020) FAOSTAT: crops. <http://www.fao.org/faostat/en/#data/QC>. Accessed 22 July 2020
- Gaitán AL, Cristancho MA, Caicedo BLC, Rivillas CA, Gómez GC (2015) Compendium of coffee diseases and pests. In: The disease compendium series of The American Phytopathological Society. APS Press, The American Phytopathological Society, St. Paul, Minnesota
- Gomes LC, Bianchi FJJA, Cardoso IM, Fernandes RBA, Filho EF, Schulte RPO (2020) Agroforestry systems can mitigate the impacts of climate change on coffee production: a spatially explicit assessment in Brazil. *Agric Ecosyst Environ* 294:106858. <https://doi.org/10.1016/j.agee.2020.106858>
- Hagggar J, Barrios M, Bolaños M, Merlo M, Moraga P, Munguia R, Ponce A, Romero S, Soto G, Staver C, Virginio E de MF (2011) Coffee agroecosystem performance under full sun, shade, conventional and organic management regimes in Central America. *Agroforest Syst* 82:285–301. <https://doi.org/10.1007/s10457-011-9392-5>
- Hope RM (2013) Rmisc: Ryan miscellaneous. R package version 1:5 <https://CRAN.R-project.org/package=Rmisc>
- International Coffee Organization (2016) The current state of the global coffee trade | #CoffeeTradeStats. http://www.ico.org/monthly_coffee_trade_stats.asp. Accessed 3 January 2020
- Jaramillo J, Setamou M, Muchugu E, Chabi-Olaye A, Jaramillo A, Mukabana J, Maina J, Gathara S, Borgemeister C (2013) Climate change or urbanization? Impacts on a traditional coffee production system in East Africa over the last 80 years. *PLoS One* 8:1–10. <https://doi.org/10.1371/journal.pone.0051815>
- Jayakumar M, Rajavel M, Surendran U, Gopinath G, Ramamoorthy K (2017) Impact of climate variability on coffee yield in India—with a micro-level case study using long-term coffee yield data of humid tropical Kerala. *Clim Chang* 145:335–349. <https://doi.org/10.1007/s10584-017-2101-2>
- Jezeer RE, Santos MJ, Verweij PA, Boot RGA, Clough Y (2019) Benefits for multiple ecosystem services in Peruvian coffee agroforestry systems without reducing yield. *Ecosyst Serv* 40:101033. <https://doi.org/10.1016/j.ecoser.2019.101033>
- Jha S, Bacon CM, Philpott SM, Ernesto Méndez V, Läderach P, Rice RA (2014) Shade coffee: update on a disappearing refuge for biodiversity. *Bioscience* 64:416–428. <https://doi.org/10.1093/biosci/biu038>
- Kath J, Byrareddy VM, Craparo A, Nguyen-Huy T, Mushtaq S, Cao L, Bossolasco L (2020) Not so robust: robusta coffee production is highly sensitive to temperature. *Glob Chang Biol* 26:3677–3688. <https://doi.org/10.1111/gcb.15097>
- Lambot C, Herrera JC, Bertrand B, Sadeghian S, Benavides P, Gaitán A (2017) Chapter 2 - cultivating coffee quality—terroir and agro-ecosystem. In: Folmer B (ed) *The craft and science of coffee*. Academic Press, pp 17–49
- Lin BB (2010) The role of agroforestry in reducing water loss through soil evaporation and crop transpiration in coffee agroecosystems. *Agric For Meteorol* 150:510–518. <https://doi.org/10.1016/j.agrformet.2009.11.010>
- Lin BB, Perfecto I, Vandermeer J (2008) Synergies between agricultural intensification and climate change could create surprising vulnerabilities for crops. *Bioscience* 58:847–854. <https://doi.org/10.1641/B580911>
- Mariño YA, Vega VJ, García JM, Verle Rodrigues JC, García NM, Bayman P (2017) The coffee berry borer (Coleoptera: Curculionidae) in Puerto Rico: distribution, infestation, and population per fruit. *J Insect Sci* 17. <https://doi.org/10.1093/jisesa/fiew125>
- Moher D, Liberati A, Tetzlaff J, Altman DG (2009) Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *PLoS Med* 6:1–6. <https://doi.org/10.1371/journal.pmed.1000097>
- Montagnon C, Cilas C, Leroy T, Yapó A, Charmetant P (2000) Genotype-location interactions for *Coffea canephora* yield in the Ivory Coast. *Agron Sustain Dev* 20:101–109. <https://doi.org/10.1051/agro:2000110>
- Muñoz-Villiers LE, Geris J, Alvarado-Barrientos MS, Holwerda F, Dawson T (2020) Coffee and shade trees show complementary use of soil water in a traditional agroforestry ecosystem. *Hydrol Earth Syst Sci* 24:1649–1668. <https://doi.org/10.5194/hess-24-1649-2020>
- Oliveira CM, Auad AM, Mendes SM, Frizzas MR (2013) Economic impact of exotic insect pests in Brazilian agriculture. *J Appl Entomol* 137:1–15. <https://doi.org/10.1111/jen.12018>
- Peterson BG, Carl P (2019) PerformanceAnalytics: econometric tools for performance and risk analysis. R package version 1(5):3 <https://CRAN.R-project.org/package=PerformanceAnalytics>
- Pham Y, Reardon-Smith K, Mushtaq S, Cockfield G (2019) The impact of climate change and variability on coffee production: a systematic review. *Clim Chang* 156:609–630. <https://doi.org/10.1007/s10584-019-02538-y>
- Pourhoseingholi MA, Baghestani AR, Vahedi M (2012) How to control confounding effects by statistical analysis. *Gastroenterol Hepatol Bed Bench* 5:79–83
- R Core Team (2019) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria <https://www.R-project.org/>
- Ratnadass A, Fernandes P, Avelino J, Habib R (2012) Plant species diversity for sustainable management of crop pests and diseases in agroecosystems: a review. *Agron. Sustain. Dev.* 32:273–303. <https://doi.org/10.1007/s13593-011-0022-4>
- Rodriguez PB, Vasquez MM (2008) Economic aspects of coffee production. In: Wintgens JN (ed) *Coffee: growing, processing, sustainable production: a guidebook for growers, processors, traders and researchers*. Wiley-VCH, Weinheim, Great Britain, pp 821–834
- Rutherford M, Phiri N (eds) (2006) *Pests and diseases of coffee in eastern Africa: a technical and advisory manual*. CAB International, Wallingford, UK
- Sarmiento-Soler A, Vaast P, Hoffmann MP, Jassogne L, van Asten P, Graefe S, Rötter RP (2020) Effect of cropping system, shade cover and altitudinal gradient on coffee yield components at Mt. Elgon, Uganda. *Agric Ecosyst Environ* 295:106887. <https://doi.org/10.1016/j.agee.2020.106887>

- Sauvadet M, van den Meersche K, Allinne C, Gay F, Melo Virginio Filho E de, Chauvat M, Becquer T, Tixier P, Harmand J-M (2019) Shade trees have higher impact on soil nutrient availability and food web in organic than conventional coffee agroforestry. *Sci Total Environ* 649:1065–1074. <https://doi.org/10.1016/j.scitotenv.2018.08.291>
- Staver C, Guharay F, Monterroso D, Muschler RG (2001) Designing pest-suppressive multistrata perennial crop systems: shade-grown coffee in Central America. *Agrofor Syst* 53:151–170. <https://doi.org/10.1023/A:1013372403359>
- Swiss Academic Software (2019) Citavi. Swiss Academic Software GmbH. www.citavi.com
- The Intergovernmental Panel on Climate Change (2019) An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. <https://www.ipcc.ch/srccl/>. Accessed 23 July 2020
- Tolessa K, D'heer J, Duchateau L, Boeckx P (2017) Influence of growing altitude, shade and harvest period on quality and biochemical composition of Ethiopian specialty coffee. *J Sci Food Agric* 97:2849–2857. <https://doi.org/10.1002/jsfa.8114>
- Vaast P, Bertrand B, Perriot J-J, Guyot B, Génard M (2006) Fruit thinning and shade improve bean characteristics and beverage quality of coffee (*Coffea arabica* L.) under optimal conditions. *J Sci Food Agric* 86:197–204. <https://doi.org/10.1002/jsfa.2338>
- Valentine JC, Thompson SG (2013) Issues relating to confounding and meta-analysis when including non-randomized studies in systematic reviews on the effects of interventions. *Res Synth Methods* 4:26–35. <https://doi.org/10.1002/jrsm.1064>
- Vega FE, Infante F, Castillo A, Jaramillo J (2009) The coffee berry borer, *Hypothenemus hampei* (Ferrari) (Coleoptera: Curculionidae): a short review, with recent findings and future research directions. *Terr Arthropod Rev* 2:129–147. <https://doi.org/10.1163/187498209X12525675906031>
- Waller JM, Bigger M, Hillocks RJ (2007) Coffee pests, diseases and their management. CABI Pub, Wallingford, UK, Cambridge, MA
- Wickham H (2016) ggplot2: elegant graphics for data analysis. Springer-Verlag, New York
- Wintgens JN (2008) The coffee plant. In: Wintgens JN (ed) Coffee: growing, processing, sustainable production: a guidebook for growers, processors, traders and researchers. Wiley-VCH, Weinheim, Great Britain, pp 1–24
- You W, Wang Z, Lu F, Zhao Y, Lu S (2017) Spectral indices to assess the carotenoid/chlorophyll ratio from adaxial and abaxial leaf reflectance. *Spectrosc Lett* 50:387–393. <https://doi.org/10.1080/00387010.2017.1335753>
- Assis BP, Gross E, Pereira NE, Mielke MS, Júnior GAG (2019) Growth response of four Conilon coffee varieties (*Coffea canephora* Pierre ex A. Froehner) to different shading levels. *J Agr Sci* 11:29. <https://doi.org/10.5539/jas.v11n7p29>
- Avinash Kumar, Simmi PS, Naik GK, Giridhar P (2015) RP-HPLC and transcript profile indicate increased leaf caffeine in *Coffea canephora* plants by light. *J Biol Earth Sci* 5:1–9
- Bagyaraj DJ, Thilagar G, Ravisha C, Kushalappa CG, Krishnamurthy KN, Vaast P (2015) Below ground microbial diversity as influenced by coffee agroforestry systems in the Western Ghats, India. *Agric Ecosyst Environ* 202:198–202. <https://doi.org/10.1016/j.agee.2015.01.015>
- Bukomeko H, Jassogne L, Kagezi GH, Mukasa D, Vaast P (2018) Influence of shaded systems on *Xylosandrus compactus* infestation in Robusta coffee along a rainfall gradient in Uganda. *Agr Forest Entomol* 20:327–333
- Dossa EL, Fernandes ECM, Reid WS, Ezui K (2008) Above- and below-ground biomass, nutrient and carbon stocks contrasting an open-grown and a shaded coffee plantation. *Agrofor Syst* 72:103–115. <https://doi.org/10.1007/s10457-007-9075-4>
- Egonyu JP, Baguma J, Ogari I, Ahumaza G, Ddumba G (2017) Host preference by the twig borer *Xylosandrus compactus* (Coleoptera: Scolytidae) and simulated influence of shade trees on its populations. *Int J Trop Insect Sc* 37:183–188. <https://doi.org/10.1017/S174275841700008X>
- Evizal R, Tohari PID, Widada J, Widiyanto D (2012) Soil bacterial diversity and productivity of coffee-shade tree agro-ecosystems. *J Trop Soil* 17:181–187
- Evizal R, Prijambada ID, Widada J, Widiyanto D, Tohari (2013) Diversity of legume nodulating bacteria as key variable of coffee agro-ecosystem productivity. *Int Res J Agric Sci Soil Sci* 3:141–146
- Guillemot J, Le Maire G, Munishamappa M, Charbonnier F, Vaast P (2018) Native coffee agroforestry in the Western Ghats of India maintains higher carbon storage and tree diversity compared to exotic agroforestry. *Agric Ecosyst Environ* 265:461–469. <https://doi.org/10.1016/j.agee.2018.06.002>
- Hajian-Forooshani Z, Kuesel R, Gonthier DJ (2018) Explaining the distribution of *Rhabdopterus jansoni* in coffee plantations: insights from diet breadth and preference. *Agrofor Syst* 92:731–738. <https://doi.org/10.1007/s10457-016-0044-7>
- Hareesh SB, Jayarama KJ (2008) Effect of integrated nutrient management practices on nutrient status and yield of robusta coffee. *J Coffee Res* 36:1–9
- Klein AM, Steffan-Dewenter I, Buchori D, Tschantke T (2002) Effects of land-use intensity in tropical agroforestry systems on coffee flower-visiting and trap-nesting bees and wasps. *Conserv Biol* 16:1003–1014. <https://doi.org/10.1046/j.1523-1739.2002.00499.x>
- Klein AM, Steffan-Dewenter I, Tschantke T (2003) Pollination of *Coffea canephora* in relation to local and regional agroforestry management. *J Appl Ecol* 40:837–845. <https://doi.org/10.1046/j.1365-2664.2003.00847.x>
- Krishnan S, Kushalappa CG, Shaanker RU, Ghazoul J (2012) Status of pollinators and their efficiency in coffee fruit set in a fragmented landscape mosaic in South India. *Basic Appl Ecol* 13:277–285. <https://doi.org/10.1016/j.baae.2012.03.007>
- Nesper M, Kueffer C, Krishnan S, Kushalappa CG, Ghazoul J (2017) Shade tree diversity enhances coffee production and quality in agroforestry systems in the Western Ghats. *Agric Ecosyst Environ* 247:172–181. <https://doi.org/10.1016/j.agee.2017.06.024>
- Okelana FA, Odebiyi JA (2007) Field parasitism of *Cephonodes hylas* linnaeus (Lepidoptera: Sphingidae), an insect pest of robusta coffee *Coffea canephora* (Pierre ex. Froehner) in Nigeria. *IFE J Sci* 9:173–176. <https://doi.org/10.4314/ijs.v9i2.32246>
- Oliosi G, Giles JAD, Rodrigues WP, Ramalho JC, Partelli FL (2016) Microclimate and development of *Coffea canephora* cv. Conilon under different shading levels promoted by Australian cedar

- (*Toona ciliata* M. Roem. var. *Australis*). Aust J Crop Sci 10:528–538. <https://doi.org/10.21475/ajcs.2016.10.04.p7295x>
- Partelli FL, Araujo AV, Vieira HD, Machado Dias JR, de Menezes T, Fernando L, Ramalho JC (2014) Microclimate and development of ‘Conilon’ coffee intercropped with rubber trees. Pesqui Agropecu Bras 49:872–881. <https://doi.org/10.1590/S0100-204X2014001100006>
- Prado SG, Collazo JA, Irwin RE (2018) Resurgence of specialized shade coffee cultivation: effects on pollination services and quality of coffee production. Agric Ecosyst Environ 265:567–575. <https://doi.org/10.1016/j.agee.2018.07.002>
- Prado SG, Collazo JA, Stevenson PC, Irwin RE (2019) A comparison of coffee floral traits under two different agricultural practices. Sci Rep 9:7331. <https://doi.org/10.1038/s41598-019-43753-y>
- Rodriguez-Lopez NF, Cavatte PC, Silva PEM, Martins SCV, Morais LE, Medina EF, Damatta FM (2013) Physiological and biochemical abilities of robusta coffee leaves for acclimation to cope with temporal changes in light availability. Physiol Plantarum 149:45–55. <https://doi.org/10.1111/ppl.12010>
- Sales EF, Mendez VE, Caporal FR, Faria JC (2013) Agroecological transition of conilon coffee (*Coffea canephora*) agroforestry systems in the State of Espírito Santo, Brazil. Agroecol Sustain Food Syst 37:405–429. <https://doi.org/10.1080/10440046.2012.712633>
- Souza GS, Alves DI, Dan ML, Lima JS d S, Fonseca ALCC d, Araujo JBS, Guimaraes LA d OP (2017) Soil physico-hydraulic properties under organic conilon coffee intercropped with tree and fruit species. Pesqui Agropec Bras 52:539–547. <https://doi.org/10.1590/s0100-204x2017000700008>
- Tumwebaze SB, Byakagaba P (2016) Soil organic carbon stocks under coffee agroforestry systems and coffee monoculture in Uganda. Agric Ecosyst Environ 216:188–193. <https://doi.org/10.1016/j.agee.2015.09.037>
- Vaast P, Raghuramulu Y (2012) Coffee quality in coffee agro-forestry systems of Kodagu, Western Ghats of India. Ind Coffee 76:10–11
- Venancio LP, Teixeira do Amaral, Jose Francisco, Cavatte PC, Vargas CT, dos Reis EF, Dias JR (2019) Vegetative growth and yield of robusta coffee genotypes cultivated under different shading levels. Biosci J 35:1490–1503. <https://doi.org/10.14393/BJ-v35n5a2019-45039>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.